THESIS – The Transiting Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft

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Executive Summary: The THESIS mission concept is a space-based, modest cost, low technical risk mission capable of characterizing the atmospheres of exoplanets, including super-Earths in the habitable zone. Building on the successes of Spitzer and the technical heritage of WISE, THESIS would be highly optimized for exquisite system stability (1 part in 10^5) and would deliver photon-noise-limited spectroscopy and photometry over the crucial 3 –12 μm wavelength range. This range of wavelengths contains signatures of water, methane, carbon monoxide, and other molecules. THESIS would be the first mission explicitly designed to characterize planets where life could exist; THESIS would profoundly advance our understanding of the physical conditions and likely the histories of exoplanets, ranging from hot-Jovians to super-Earths. THESIS would accomplish these objectives because a dedicated exoplanet mission permits optimization that allows a modest telescope to compete with much larger, general-purpose missions. By providing a detailed characterization of exoplanets detected by transit surveys, this mission is a logical "next-step" to missions such as Kepler and Corot, as well as ground-based transit survey programs. A focused and relatively low-cost mission such as THESIS has a unique and significant discovery space and could serve as a stepping stone to more ambitious exoplanet missions.

The THESIS concept is intended to be a simple, modest cost, low risk mission that can significantly advance the state-of-the-art for exoplanet characterization, including the study of worlds where life could exist.

Mission Overview: THESIS is envisioned as a 40-60 cm infrared telescope cooled to ~60 K with a mission life of ~1–5 years. Equipped with a highly optimized instrumentation, THESIS would provide photon-noise-limited, low-resolution spectra from 3–12 μm up to a dynamic range of 10^5:1. This would dramatically exceed the dynamic range of the current Spitzer exoplanet spectroscopy measurements. Although the sensitivity limit for THESIS depends on spectral resolution, eclipse length, and spectral type, the mission is well designed to characterize Kepler and ground-based transit targets; for example, THESIS measurements of a relatively faint magV = 14 M0 star would have an estimated photon-noise-limited SNR of between 10^4 and 10^3, depending on wavelength. The primary difficulty for high-dynamic-range spectroscopy is system stability, not a lack of photons. Analysis of Spitzer results shows that the key elements to achieve the instrument stability goal for THESIS of one part in 10^5 or better requires a highly optimized instrument desing. These goals **do not require new technology**, and similar performance has been demonstrated on flight systems. Thus, the technology risk for the key elements of THESIS is low.

Background: The Spitzer Observatory has revolutionized the observational characterization of exoplanets by detecting infrared light emitted from these objects. Broadband, photometric measurements have been reported for HD 209458b (Deming et al. 2005), TrES-1 (Charbonneau et al. 2005), HD 189733b (Deming et al. 2006), and υ Andromeda b (Harrington et al. 2006). The impact of these measurements on our understanding of exoplanets is difficult to overstate. Numerous theoretical results have been presented to interpret the observations (Burrows et al. 2006, Barman et al. 2005, Cooper and & Showman 2005, Fortney et al. 2005, Seager et al. 2005, and references therein). Recently, the mid-infrared spectrum of HD 209458b and HD 189733b has been measured with the IRS instrument (Richardson et al. 2007, Swain et al. 2007 Grillmair et al. 2007); these results demonstrate conclusively that the era of exoplanet spectroscopy has arrived.

It is difficult to overstate the impact of the Spitzer detection of emission originating from extrasolar planets. These unprecedented measurements have generated great interest among both professional astronomers and the general public. As a young and dynamic field, exoplanets continue to surprise us; recent examples of this include (1) observations of υ Andromeda b showing that emission on the dayside and nightside differs dramatically (Herrington et al. 2006), and (2) spectra of HD 209458b (Richardson et al. 2007; Swain et al. 2007) and HD 189733b (Grillmair et al. 2007), which all show a relatively flat spectrum. We are just entering the era of exoplanet spectroscopy with the Spitzer/IRS instrument that, tragically, has less than two years of expected life at the time of this writing.

The Kepler mission and ground-based transit surveys will greatly increase the number of known transiting planets. The next phase in the advancement of exoplanet science will be the characterization of the exoplanets discovered by the existing and planned surveys; these surveys will generate the THESIS target set. High-dynamic-range infrared spectroscopy of transiting and non-transiting planets (as demonstrated by the observations of υ Andromeda b) is a method with modest cost and low technical risk for determining atmospheric conditions, atmospheric composition, and surface composition of rocky exoplanets; infrared spectroscopy of these objects would also provide insights into likely formation histories. Differences in the atmospheric conditions and chemistry between the dayside and the nightside are especially important for the characterization of the expected "super-Earths", which are expected to exist in the habitable zone around M stars. The THESIS mission is designed to answer these and other high-impact exoplanet-related questions and to do so for the modest cost and minimal technical risk.

Existing Limitations: Characterizing exoplanets through time series photometry (including the secondary eclipse method) requires observations with a dynamic range of at least 1000:1 to detect the exoplanet emission with a SNR of a few. The dynamic range required depends on the spectral type of the stellar primary, the planet's orbital period, the planet's albedo, the exoplanet orbital phase, the wavelength of the observations, and other parameters. A dynamic range of 1,000:1 is adequate to begin the spectral characterization of hot-Jovians around a solar-type star (Richardson et al., Grillmair et al., Swain et al.); a dynamic range of ~ 10,000:1 is expected to be adequate to characterize a "super-Earth" orbiting an M star. The THESIS dynamic range goal of ~ 100,000:1 would enable high SNR characterizations of a wide variety of exoplanets.

Most astronomical instruments are designed for sensitivity, not dynamic range (bright-object SNR). As a consequence, high-SNR measurements of exoplanets using time series photometry techniques are currently limited by instrument systematics. Rapid readout and internal stability are frequently difficult for space infrared telescopes. For example, HST/NICMOS, with a grism to observe HD 189733b during secondary eclipse, has an estimated duty cycle of ~7 %; this limitation is due to difficulties with rapid readout. Spitzer, the most successful instrument for exoplanet characterization, has several systematic errors that include pointing, background contamination, charge trapping, and detector fringing. One difficulty with Spitzer (and other planned instruments) is that no on-board calibration exists to monitor the changes in the instrument systematics. Thus, calibrated instrument stability for spectroscopy at the level of one part in 10^4 may not be feasible with existing or planned instruments; spectroscopy at the level of one part in 10^5 (the goal for THESIS) is likely to be well beyond what existing or planned instruments will be capable of.

Ground-based observations cannot replace space-based measurements in the THESIS wavelength range of 3–12 μm. Not only is the Earth's atmosphere opaque in portions of this spectral range, but, at wavelengths in this region where ground-based spectroscopy is possible, the thermal emission and fluctuations due to the Earth's atmosphere prevent spectroscopy at the 10^4–10^5 level of precision. Attempts to detect exoplanet emission using the secondary eclipse method from the ground have not been successful (Richardson et al. 2003a; Richardson et al. 2003b; Deming et al. 2005), and the only successful secondary eclipse photometry experiment from the ground (Snellen 2006) achieved very low SNR and strengthens the case for space-based observations. While ground-based observations should certainly be pursued, they cannot be expected to make the detailed infrared characterization of exoplanets possible with a dedicated space mission.

Implementation concept: We have worked out a design that seems feasible employing a relatively small telescope. For photon-noise-limited time series photometry detection methods, such as the secondary eclipse method, the signal-to-noise (SNR) scales ~ N/sqrt(N) = sqrt(N) so that the *theoretical* sensitivity improves with telescope diameter (not area). High-dynamic-range spectroscopy requires specialized instrument design. Although collaborations are welcomed at this time, THESIS is a tightly focused mission; *we encourage collaboration discussions with individuals or institutions consistent with a mission emphasis on simplicity, low technical risk, and modest cost.*

Community Access: The THESIS observing model is a GTO/GO mix. Significant observing time (approximately half) would be reserved for the science team with the balance of time devoted to open proposals (excluding reserved objects) from the community. The kinds of exoplanet programs that are possible with THESIS include spectroscopy, orbital phase resolved spectroscopy, eclipse mapping, and searching for spectral changes or variability. Given the large number of potential targets expected from transit surveys (~1000 from Kepler alone), we expect a large and rich target set for both GTO and GO observations. Also, THESIS can measure the day-night contrast on non-transition planets (as has been done for υ Andromeda b) that further extends the target set possible with THESIS.

Discovery space: The scientific objective of THESIS is to determine the physical and chemical properties of exoplanets, including dynamical processes and dayside to nightside differences. For the giant planets, THESIS would characterize the atmosphere, while for rocky planets it would characterize the surface. For "super Earths" in the habitable zone, THESIS would determine if these planets are actually hospitable for life as we know it. The unique discovery space for THESIS is based on (1) quality of the spectra, (2) spectra as a function of orbital phase, and (3) number of targets. Because of the optimized instrument design, THESIS would be uniquely stable and capable of measuring spectra with higher SNR than instruments that are not optimized for this type of observation. The on-board calibration system also makes it possible for THESIS to measure and compare spectra taken at different orbital phase angles; thus, the nightside and dayside emission could be compared at high SNR. Finally, because of the focused science objectives of this mission, THESIS could devote more time to exoplanet characterization than a general-purpose mission. This is not only beneficial for observing large numbers of exoplanets. A dedicated, high-SNR spectroscopy mission creates the possibility of looking for changes in the exoplanet emission. For example, THESIS could answer the question "do we see evidence of changes in the dayside emission?" Because THESIS would be focused on exoplanet characterization, it could observe a large number of exoplanet targets (~ 700 targets per year for a 10-hour observing sequence). THESIS would also be capable of repeated eclipse mapping (measuring departures from the expected shape of the light curve during ingress and egress); this would enable searching for temporal and spatial changes in the emission originating from an exoplanet.

Summary: THESIS should be started now; it has a low technical risk and a high scientific payoff. A dedicated, modest cost, space mission for infrared exoplanet spectroscopy is the natural "next step". Such a mission, based on highly optimized instrumentation, would be able to characterize hundreds of transiting exoplanets, including many of those found by the Corot and Kepler missions. A highlight of the mission would be characterizing the atmosphere, and perhaps the surface, of "super-Earth" words in the habitable zone. For the Jovian-class planets, this mission would give us a highly detailed understanding of the physical conditions, chemistry, dynamics, and time variability of giant planet atmospheres. The mission results would ignite the imagination of professional astronomers and the public. Significantly, the mission would serve as a scientific and technological stepping stone to a future "grand challenge" scale mission to study Earth-like planets around other stars.

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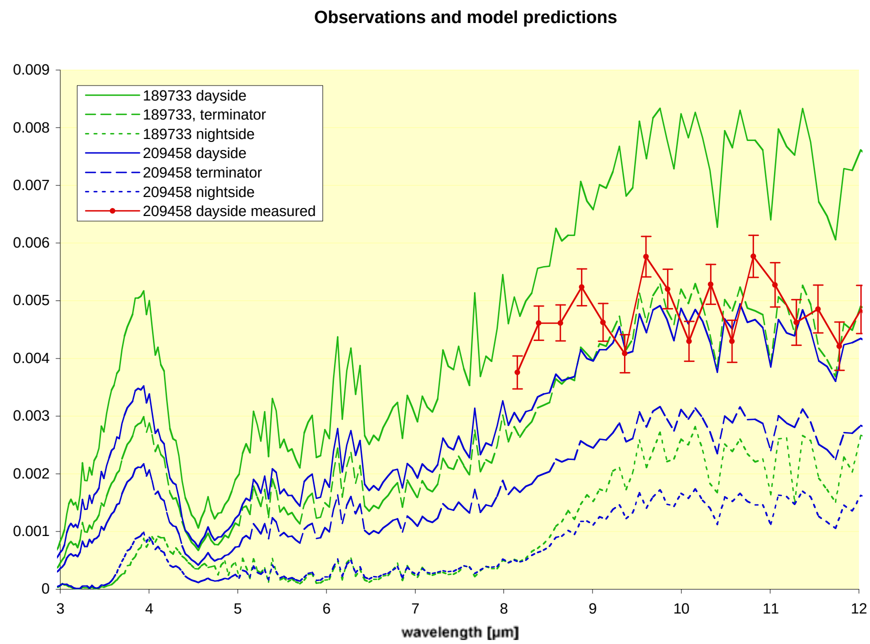

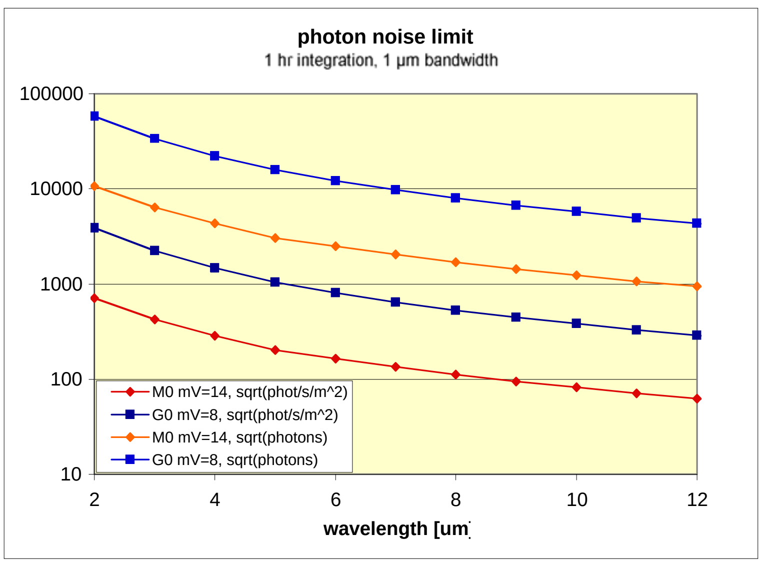

Fig 1a (top): Models (Burrows et al. 2006) for emission from the exoplanets HD 209458b (blue) and HD 189733b (green) for the view of the planet centered on the dayside, terminator and nightside (solid, dashed, and dotted lines, respectively). The wavelength limits on this plot approximately match the THESIS measurement range. Our IRS detection (Swain et al. 2007) of the dayside spectrum of HD 209458b,using Spitzer, is plotted in red. THESIS would be able to make high-SNR spectra of both the day and night side (enabled by on-board calibration) of transiting exoplanets. **Fig 1b (bottom):** The photon noise limit for a M0 magV=14 star and a G0 mavV=8 star in units of sqrt(photons/m^2/s) and for THESIS in units of sqrt(photons). For this estimate, the spectral resolution is one micron and THESIS net transmission and integration time are 0.25 and 1 hr, respectively.